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Review of solar cooling methods and thermal storage options

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ABSTRACT

Power shortage and unstable power supply remain serious problems. Conventional cooling technologies that utilize harmful refrigerants consume more energy and cause peak loads leading to negative environmental impacts. As the world grapples with the energy and environmental crisis, there is an urgent need to develop and promote environmentally benign sustainable cooling technologies. Solar cooling is one such promising technology, given the fact that solar energy is the cheapest and widely available renewable energy that matches the cooling load requirements. Thermal storage systems are essential to overcome the disadvantage of the intermittent nature of solar energy and variation in cooling demand. The enhanced utilization of solar energy and other consequences of thermal storage integrated systems have gained the attention of researchers in the recent years. This paper reviews research articles in the field of solar cooling techniques, solar collectors, storage methods and their integration, along with performance improvement studies reported using thermal stratification and cascaded thermal storage systems.

Contents

1. Introduction

Energy is vital for the progress and development of a nation's economy. Energy shortages and variable power availability cripple society's advancement. Refrigeration and air conditioning consume enormous energy. In recent years, these sectors have witnessed manifold growth, and have become essential not only for human comfort but also for a variety of applications, such as food preservation. Nearly 30% of all fresh produce, in developing countries like India, are lost due to lack of cold storage facilities and unavailability of regular power supply. Providing thermal cooling would minimize post harvest losses. Conventional cooling technologies are energy intensive and also the emission of gases used in the refrigeration systems affect the environment. Reducing energy consumption and use of sustainable energy technologies are vital to meet the increasing cooling demand in an environmentally friendly manner.

Abbreviations: TES, thermal energy storage; SHS, sensible heat storage; PCM, phase change material; PV, photovoltaic; COP, coefficient of performance; LPG, liquefied petroleum gas; HTF, heat transfer fluid; TR, tonnes of refrigeration; CPC, compound parabolic collector; LHTS, latent heat thermal storage; CTES, cool thermal energy storage; SERT, school of renewable energy technology; AHU, air handling unit.

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Depending on the application, different temperature zones need to be maintained. Consequently there is a need for a wide range of refrigeration systems. Solar cooling serves the cold storage needs in industries as varied as hospitality, pharmaceuticals, chemicals, dairy and food processing, besides serving the residential and office air conditioning needs. Solar cooling depends primarily on solar energy, either by hot water production through solar collectors or electricity production through photovoltaic panels. In comparison with conventional electrically driven compression systems, substantial primary energy savings can be expected from solar cooling, thus aiding in conserving energy and preserving the environment. Another advantage of using solar energy is that the cooling demand is highest when the solar intensity is at its highest; however, the problem with solar energy is its intermittent nature. Thermal storage is, therefore, critical.

The thermal energy storage (TES) system is one of the most appropriate methods of correcting the mismatch that occurs between the supply and demand of energy. Heat can be stored in sensible/latent form, and by thermo chemical techniques. In sensible heat storage (SHS), thermal energy is stored by raising the temperature of a solid or liquid. SHS systems utilize the heat capacity and change in temperature of the material during the process of charging and discharging. SHS characterized by temperature variation is a simpler technique, but occupies a larger volume. The amount of stored energy depends on the specific heat of the medium, temperature change and the amount of storage material. The latent heat storage is based on heat absorption or release when a phase change material (PCM) undergoes a phase change. The latent heat storage by PCM in comparison with SHS, possesses a greater density of stored energy and operates in a narrower operational temperature range. Zalba et al. [1] have reviewed various aspects of latent heat storage systems, such as PCMs heat transfer and applications. PCMs are advantageous for the dynamic and static storage of thermal energy as they absorb and release large amounts of energy at specific temperatures. However, the low thermal conductivity of PCMs and the losses associated with thermal storage, are its disadvantages. In thermo-chemical heat storage systems, the heat is stored in an endothermic chemical reaction. A detailed description on various aspects of thermal storage systems are presented by Dincer et al. [2].

The performance of the storage system and the collectors are usually affected by the degree of thermal stratification that can be maintained in the storage unit. Mixing of stored energy at different temperatures has an adverse effect on the system performance. The improvement in the storage efficiency results in a higher performance of the overall system and thermal stratification is commonly used for this purpose.

Thermal storage is an environmentally friendly technology that aids in shaping end-use demand economically. It enhances a fraction of the renewable energy utilization and energy efficiency of conventional systems. Energy storage has recently attracted increasing attention in many industrial and commercial applications. This paper illustrates the different types of solar collectors, storage methods, and performance improvement studies carried out through stratification in the storage tank, employed by the researchers in different types of solar absorption cooling systems. The suitability of the PCM based cascaded storage system for solar cooling is also studied and presented in this paper.

2. Solar cooling methods

Solar cooling offers a wide variety of cooling techniques powered by solar collector-based thermally driven cycles and photovoltaic (PV)-based electrical cooling systems. Since solar energy is time-dependent, the successful utilization of all these systems is to a very large degree dependent on the thermal storage units employed. The various stages of thermal storage integrated solar cooling systems are shown in Table 1.

At present, the exorbitant pricing of PV panels makes the use of solar thermal energy promising. The higher source temperature obtained with solar concentrators that occupy a lesser area leads to an increased coefficient of performance (COP) and reduction in the total cost of the system. Some of the comparisons studies carried out by various researchers on different solar techniques are presented. Kim and Infante Ferreira [3] have listed a variety of ways to use solar energy for refrigeration. They have ranked absorption and adsorption comparable in terms of their reported performance, and indicated that desiccant and ejector systems are more expensive. Tsoutsos et al. [4] have stated that absorption has the highest market penetration. While desiccant has large potential for market penetration, adsorption coolers have significantly lower penetration. They have also concluded that solar driven cooling systems are not competitive at the present prices. This paper reviews various solar cooling technologies, incorporating thermal storage, its challenges and potential benefits.

An assessment of solar cooling technologies based on cost, and performance parameters in addition to important boundary conditions of weather and cooling demand was presented by Mokhtar et al. [5]. Rodriguez Hidalgo et al. [6] compared the solar absorption system with a conventional vapour-compression machine system based on its performance, economic investing, energy and economic savings, and environmental impact reduction. They described an experimental research conducted on a 50 m^2 flat-plate solar collectors driven single-effect commercial LiBr/H_2O absorption machine through a hot-water storage tank that produces 6–10 kW cooling power with a generator driving power input of 10–15 kW, achieving a mean cooling period of 6.5 h of complete solar autonomy.

Calise [7] has suggested a public promoting policy (e.g., feed-in tariffs), to encourage the commercialization and economic profitability of solar-assisted heating and cooling systems. From the techno-economical analyzes (Abdullah et al. [8]) of the H_2O–NH_3–H_2 absorption cooling machine powered by different energy sources, it was found that conventional electricity from a grid is still the best form of energy source for short-term applications, and that, at locations with a constant LPG supply, LPG is attractive. However, in spite of the high initial cost, for long-term consideration, solar energy is more attractive because of its zero-fuel cost and environmentally friendly nature. Warren et al. [9] have pointed out that in new chiller development, critical attention must be paid to reducing the parasitic power consumption and improving the COP of the absorption chillers if cost competitiveness is to be obtained. Papadopoulos et al. [10] have highlighted the need to promote solar cooling in view of the positive features based on considerations of ozone depletion potential, global warming potential, primary energy ratio and life-cycle analysis.

3. Solar collection and storage

In recent years, there is a sudden demand in the utilization of solar energy for various applications. The solar collection and storage system consists of a solar collector connected through pipes to the heat storage. Solar collectors transform solar radiation into heat and transfer that heat to the heat transfer fluid (HTF) in the collector. The hot fluid is then stored in a thermal storage unit to be subsequently utilized for various applications such as absorption cooling systems. The performance of solar collection can be enhanced by better stratification in the storage tank. In the present review various stages and stratification methods adopted by researchers are studied and reported. The stratification in the

Table 1
Stages and options in solar cooling techniques.

Source	Conversion	Thermal storage (hot energy)	Production of cool energy	Thermal storage (cool energy)	Applications
Sun	Solar Thermal 1. Flat plate collector 2. Evacuated tube collector 3. Concentrated collector	1. Sensible 2. Latent 3.Thermo chemical	1. Absorption (i) Half effect (ii) Single effect (iii) Double effect (iv) Triple effect 2. Adsorption 3. Desiccant 4. Ejector	1.Sensible 2.Latent 3.Thermo chemical	1. Air conditioning (i) Office (ii) Hotel (iii) Building (iv) Laboratory 2.Food preservation (i) Vegetables (ii) Fruits (iii) Meat and Fish
	Solar PV (electrical)		Vapor compression Thermoelectric		3. Process industries (i) Dairy (ii) Pharmaceutical (iii) Chemical

storage tank enhances the solar collector efficiency; the studies reported in the literature are detailed in the subsequent sections.

3.1. Solar collectors

A variety of solar collectors are used as a heat source for thermally driven refrigeration processes. Solar collectors are broadly classified as, non-concentrating and concentrating type collectors. Flat-plate collectors are the most widely used kind of collectors in the world. Non concentrating collectors are cheaper, but produce temperatures sufficient only for less efficient single effect/half effect absorption machines. Balghouthi et al. [11,12] have modeled solar-powered absorption cooling technology under Tunisian conditions, using the TRNSYS. Their optimized system for a typical building of 150 m^2 comprised of a water lithium bromide absorption chiller of a capacity of 11 kW, a 30 m^2 flat plate solar collector area tilted 35° from the horizontal, and a 0.8 m^3 hot water storage tank. Rosiek et al. [13] have analyzed a solar-assisted air-conditioning system installed in the Solar Energy Research Center (CIESOL) building, in an area of 110 m^2. The system consists of 160 m^2 flat-plate solar collectors, two storage tanks with a capacity of 5000 L, one each to promote good thermal stratification and to operate a 70 kW of cooling capacity single effect LiBr–H_2O absorption chiller. It produced average values of the COP and a cooling capacity of 0.6 and 40 kW during the summer months. The performance analysis and experimental results of 40 TR cooling capacity water-lithium bromide absorption chillers for an office building run by 300 m^2 flat plate collectors and an oil-fired supplementary thermal energy source have been described by Ayyash et al. [14]. The system consists of a 20 m^3 of hot water reservoir. It has reported a saving in the range of 25–40% when compared to an equivalent conventional water-cooled air conditioner. Koca et al. [15] performed energy and exergy analyses for a flat-plate solar collector with a PCM-filled tank. They found that the net energy efficiency was higher than the net exergy efficiency.

To obtain higher temperatures, anti-reflective coating, double glass, and vacuum tube collectors are adopted. Marc et al. [16] presented a comparison of the simulation of the double glazing solar collector and stratified tank dynamic model results, with real scale solar experimental data taken from solar cooling installation. The modeling and simulation of the absorption solar cooling system was carried out with the TRNSYS program by Assilzadeh et al. [17]. The optimum system for Malaysia's climate for a 3.5 kW (1 refrigeration ton) system, consists of a 35 m^2 evacuated tubes solar collector sloped at 20 °C with a 0.8 m^3 storage tank. Agyenim et al. [18] have developed and tested a domestic-scale prototype solar cooling system based on a LiBr/H_2O absorption system. The system consisted of a 12 m^2 vacuum tube solar collector, a 4.5 kW LiBr/H2O absorption chiller, a 1000 L cold storage tank and a 6 kW fan coil. The system produced an electrical COP of 3.6 with chilled water temperatures at 7.4 °C. Ali at al. [19] have described the performance assessment of an integrated cooling plant with combined free cooling and solar-powered single-effect lithium bromide-water absorption chiller of 35.17 kW cooling that includes vacuum tube collectors with gross and net areas of 108 m^2 and 72 m^2 respectively, a hot water storage capacity of 6.8 m^3, a cold water storage capacity of 1.5 m^3 and a 134 kW cooling tower. The plant provides air-conditioning for a floor space of 270 m^2. The energy balance of a single-effect (LiBr/H_2O) absorption chiller of 35 kW nominal cooling capacity driven by hot water delivered from a 49.9 m^2 array of flat-plate collectors has been presented by Syed et al. [20]. Thermal energy was stored in a 2 m^3 stratified hot water storage tank. The average COP was 0.34–0.6.

Concentrating collectors produce sufficiently high temperature to drive efficient multi effect absorption machines, but require tracking, which is costlier and requires additional installations. Some of the parabolic trough concentrators connected to absorption chillers have been presented by Fernadez Garcia et al. [21]. Tierney [22] in his simulations on the comparison of energy saving by a solar assisted cooling system with gas firing has obtained 39% for a combination of a single effect chiller and trough collector; 32% for a double-effect chiller and flat-plate collector; 86% for a double-effect chiller and trough collector. Florides et al. [23] have presented the modeling, simulation and total equivalent warming impact of a domestic size absorption solar cooling system. The system modeled with the TRNSYS provided a final optimized system of 15 m^2 compound parabolic collector (CPC) and 600 L hot water storage tank for a 11 kW cooling capacity water–LiBr absorption chiller. The linear fresnel collector is increasingly gaining attention for integration with highly efficient absorption chillers

However, the successful utilization of these systems is to a very large degree dependent on the energy storage units employed. The simulation of a solar LiBr–H_2O cooling system with a trough collector by Mazloumi et al. [24] showed that the collector mass flow rate has a negligible effect on the minimum required collector area, but it has a significant effect on the optimum capacity of the storage tank. Once the characteristics of the end-use demand and nature of the energy source options are known, the total demand and supply in the time domain have to be brought together through the integration of an efficient energy storage and distribution network. Hence, the commercial and economics of solar thermal utilities or devices are tied to the design of an efficient thermal storage system to meet the time-dependent supply and end-use requirements.

3.2. Storage methods

Thermal energy storage can be achieved in the form of the sensible heat of a solid or liquid medium, the latent heat of a phase

change substance, or by a chemical reaction. The choice of the storage medium depends on the amount of energy to be stored in unit volume, or the weight of the medium, and the temperature range at which it is required for a given application. The sensible heat storage units that use water, oil or pebble beds have very low heat capacity per unit volume. On the other hand, the latent heat thermal storage (LHTS) unit is particularly attractive, due to its high-energy storage capacity, and its isothermal behavior during the charging and discharging process. There are various studies carried out by researchers on the integration of the thermal storage system with vapor absorption refrigeration system.

In solar vapor absorption systems, the energy received from the solar collector is given as a heat input to the generator. The availability of solar energy is intermittent and also of non-uniform intensity, hence the energy has to be stored for a uniform heat supply to the generator. Thermal storage therefore plays a vital role in solar based systems. There are different ways through which heat energy can be stored:

(a) External heat storage:
  (1) Storing hot energy for supply to the generator.
  (2) Storing of produced cool energy
(b) Internal storage
  In external thermal storage systems, the HTF from the solar collectors will be circulated to the hot thermal storage tank to store energy for later use.

An SHS system consists of a storage medium, a container and input/output ports. Containers must retain the storage material and prevent loss of thermal energy. The performance of SHS systems is influenced by factors, such as the thermal capacity of the fluid used, the operating temperature range, the design and geometry of the inlet and outlet ports, the mixing introduced during the charge and discharge cycles, thermal losses from the storage device and the degree of thermal stratification in the storage device. Several studies have been described in the literature to investigate and analyze thermal stratification in storage tanks. These studies have shown that improving thermal stratification in the storage device causes a substantial improvement in the whole system efficiency compared to the thermally mixed storage tank. Hence, a detailed study has been carried out on the stratification studies of the researchers, and it is reported separately at the end of this section.

Dincer et al. [25] presented a detailed investigation of the availability of SHS techniques for solar thermal applications, selection criteria for SHS systems, and the economics and environmental impact of SHS systems. Another method of SHS is the use of a packed bed of solids for storing thermal energy. The packed bed provides an effective means of energy storage for many systems and has been satisfactorily employed for various applications. Beasly and Clark [26] summarized the status of the SHS modeling of packed beds, including numerical investigations. Saez and Mcoy [27], Torab and Beasley [28] and Sozen [29] studied the performance of packed bed SHS systems using one-dimensional separate phase's models.

The temperature requirement for the generator will be different depending on the type of vapor absorption system (half/single/double/triple effect). However, for all these systems, heat has to be supplied within a narrow operating temperature range of 5–10 $^\circ$C for better performance. Hence, storing a large quantity of heat within a narrow temperature range in a sensible heat form requires a large volume storage tank. This type of sensible heat storage tank may be useful only for the purpose of providing uniform heat flux to the generator, irrespective of fluctuations in solar radiation intensity. Sensible heat storage is not capable of providing a large quantity of heat required for the generator during non-sunshine hours. Latent heat storage systems are capable of storing a large quantity of heat in smaller volumes and have isothermal behavior during the heat retrieval process. Hence, the problem encountered in sensible heat storage is avoided in a latent heat storage system that can supply heat to the generator at an approximately constant temperature for a longer duration even during non-sunshine hours.

A good understanding of the heat transfer processes involved in an LHTS unit is essential for accurately predicting the thermal performance of the system, and for avoiding a costly system design. Solidification and melting are important phenomena in thermal storage applications. A lot of researchers have conducted experimental investigation to predict the transient thermal performance of LHTS units with different configurations and for various operating conditions. Adine and Qarnia [30] have presented a numerical analysis of the thermal behavior of a shell and tube latent heat storage unit, using single and two PCMs. Their analysis showed that the maximum thermal storage efficiencies of the two latent heat storage units are identical, irrespective of the HTF inlet temperature.

Agyeneim et al. [31] compared the performance of a multitube system with that of a single tube shell and tube system to power a $LiBr/H_2O$ absorption cooling system. The multitube system improved the heat transfer rate during charging, and produced an output temperature suitable to operate the cooling system, but showed large sub cooling. Medrano et al. [32] experimentally investigated the heat transfer process during the melting and solidification of the PCM in five small heat exchangers, working as latent heat thermal storage systems. The highest average thermal power was obtained for the PCM filled compact heat exchanger, while the PCM-matrix in the double pipe heat exchanger possessed average power per unit area.

A transient heat transfer phenomenon during the charging and discharging of the shell-and-tube latent thermal energy storage system was analyzed by Trp et al. [33]. Akgun et al. [34], investigated the effect of increasing the HTF inlet temperature and mass flow rate. The results show a 30% decrease in the total melting time of the paraffin. A poor heat transfer rate linked with the PCM in the shell and tube heat exchanger restrains its wide application. A packed bed consisting of the PCM contained in spherical shells, offers the advantage of a higher heat transfer rate due to a larger heat transfer area and larger storage density.

Wu and Fang [35] analyzed the thermal characteristics of a packed bed containing spherical capsules, used in a latent heat thermal storage system with a solar collector. They have also dealt with the influences of the inlet temperature of the HTF, the flow rate of the HTF and the initial temperatures of the HTF and the PCM, on the latent efficiency and heat release rate. Felix Regin et al. [36] numerically investigated the effects of the HTF inlet temperature, the mass flow rate, the phase change temperature range and the radius of the capsule on the dynamic response of a packed bed latent heat thermal energy storage system using spherical capsules for both the charging and discharging modes. Nallusamy et al. [37] have investigated the thermal performance of a packed bed combined sensible and latent heat storage unit, integrated with the solar flat plate collector. They have highlighted the advantageous feature of a uniform rate of charging and discharging of a combined storage system for a longer period.

3.3. Stratification in TES

Thermal storage is a very important link in any solar thermal supply network. Thermal stratification denotes the formation of horizontal layers of a fluid of varying temperatures with the warmer layers of fluid placed above the cooler ones. In a highly stratified storage, the return temperature to the solar collector is lowered leading to an increased efficiency of the solar collector. Collectors capitalize on low temperature heating with reduced heat loss leading to maximum heat gain from solar energy. Several stud-

ies have been carried out by researchers on the sensible heat storage systems to improve the overall efficiency of the storage system and collection. Thermal stratification holds the key for the effective charging and discharging of the energy stored.

Most of the models proposed in the literature are for simple one-dimensional cases. Zurigat et al. [38] have carried out a survey of the stratified thermal storage one-dimensional models available in the literature. They have validated six models with the experimental data, obtained at their laboratory and from the literature, conducted under both constant and varying inlet fluid temperature conditions. The models include the fully stratified storage tank model, a modified version of this model, the viscous entrainment model and the effective diffusivity model. The models showed varying degree of agreement with the thermocline test data. Ghadder et al. [39] have examined a one-dimensional problem using a numerical finite difference method. They showed that the turbulent mixing factor is greatly dependent on the flow rate, the inlet port design, and the thermocline location in the tank.

Thermodynamic benefits, especially the increase in exergy storage capacity obtained by stratification, and the use of the exergy analysis for storage comparisons have been highlighted by Rosen et al. [40]. They have further indicated that the increase in the exergy capacity is the greatest for storages at temperatures close to the environment temperature. The exergy analysis by Jack and Wrobel [41] has shown that stratification delays the mixing of the incoming fluid with that in the storage tank, leading to an increase in the overall second-law efficiency and a reduction in the optimum charging time compared to the fully mixed case. The effects of different parameters and dimensionless numbers that influence and characterize stratification have been analyzed by various investigators. [42,43]. The dimensionless group analysis shows that the Richardson number is generally used as the evaluate index. Aspect ratio is one of the critical parameters to obtain stratification. Lack of improvement in thermal extraction efficiency by increasing the ratio of length to diameter ratios larger than 4, has been found by Al-Marafie et al. [44] in their experiment on the effect of tank geometry on a pressurised thermal storage tank. Ievers and Lin [45] analyzed stratification in a storage tank using Fluent software, and concluded that increasing the tank's height/diameter aspect ratio, decreasing the inlet/outlet flow rates and moving the inlet/outlet to the outer extremities of the tank, results in increasing levels of thermal stratification. Andersen et al. [46] presented the thermal behavior of three different modern stratifiers with fabric and rigid pipes. The effectiveness of stratifiers especially at low flow rates has been shown by Shah et al. [47] through Computational Fluid Dynamics and Particle Image Velocimetry and temperature measurements. The introduction of obstacles also improves thermal stratification. [48].

Stratification improvements by PCMs have also been reported by different investigators. Cabeza et al. [49] showed that the energy density of the hot water storage tank with stratification, increased with increasing amounts of the PCM module at the top of the tank. By means of simulation and experimental works on PCM integrated hot water stores, Mehling et al. [50] showed an improvement in the energy density, reheating and delay in heat loss of hot water stores.

4. Absorption cooling technologies

In sorption systems the refrigerant effect is produced due to physical and/or chemical changes that occur between the refrigerant and the sorbent. They are broadly classified as closed and open sorption systems. Absorption and adsorption are two types of closed sorption systems, in which the absorption system encounters a change in phase of the sorbent, whereas in an adsorption system, the sorbent undergoes no change in phase. In open sorption systems, desiccants are used to dehumidify the air. Hence, it is commonly called a desiccant cooling system. A review of the research of the state-of-the-art solar sorption (absorption and adsorption) refrigeration technologies was presented by Fan et al. [51]. Ziegler [52] has discussed different issues in increasing the efficiency of open and closed sorption systems, and making solid and liquid sorption systems economically competitive. For sorption technology to be ecologically competitive, highly efficient systems are required to cope with the increasing efficiency of compression systems and power plants. Mugnier et al. [53] have compared different sorption systems, such as absorption, adsorption and solid/gas reaction, in relation to their storage capacity, especially for solar cooling applications. The comparison points out that for negative temperatures, solid/gas reaction with ammonia has the best capacity, while storage with the PCM appears to be competitive, even if a little less efficient. For positive temperatures, the best storage capacity is for water (working fluid) in absorption with NaOH as the absorbent, and in reaction with $CaCl_2$, $MgCl_2$ and Na_2S as salt. The various studies carried out by researchers on these technologies are classified and summarized in this section.

In an absorption refrigeration system, the refrigerant vapor is drawn from the evaporator by absorption into the absorbent. The addition of thermal energy to the generator liberates refrigerant vapor from the strong solution. The refrigerant gets condensed in the condenser by rejecting the heat. The liquid refrigerant is then expanded to the evaporator and the cycle is completed. Solar based absorption chillers are thermally activated refrigeration systems that draw heat from a storage tank connected to a solar collector to operate the absorption chiller. Based on the thermodynamic cycle of operation and solution regeneration, they are classified as half, single and multi-effect chillers. Half and single effect chillers are hot water driven systems that require relatively lesser hot water temperatures when compared to multi-effect systems. A half effect cycle takes the heat input at two pressure levels. The condenser and evaporator operate at high and low pressures. The vapour generated at an intermediate pressure is fed to a second absorber, which feeds the generator at high pressure. The heat available at the same temperature is sufficient for both the generators.

Single effect absorption chillers are based on the basic absorption cycle that contains a single absorber and generator as shown in Fig. 1. A low cost non-concentrating flat plate or evacuated tube solar collector is sufficient to obtain the required temperature for the generator. Though economical, its COP is lower. For obtaining a higher COP, multi-effect chillers such as double and triple effect absorption chillers are used, which are run by steam produced from concentrating solar collectors. Double and Triple effect chillers are costlier but energy efficient. Multi-effect chillers employ an additional generator and heat exchanger to liberate the refrigerant from the absorbent solution with lesser heat input. The available solar intensity, cooling capacity requirements, overall performance and cost, determines the selection of a particular configuration. Gebreslassie et al. [54] conducted an exergy analysis of different water-LiBr absorption cycles. They showed that half effect followed by single effect cycles had the lowest maximum exergy efficiencies, while double and triple effect cycles had the highest efficiencies. Kim and Infante Ferreira [55] have compared theoretically, the performance of a direct and indirect air-cooled absorption chiller. They have pointed out that the direct air-cooled chiller design was preferable in terms of energy efficiency.

Li and Sumathy [56] stressed the importance of the generator inlet temperature, chiller, collector choice, system design and arrangement, in the design and fabrication of a solar powered air-conditioning system. Srikhirin et al. [57] have discussed a number of absorption refrigeration systems and related research options. In this section, literatures pertaining to the improvement of absorption cooling systems, theoretical and experimental studies on solar

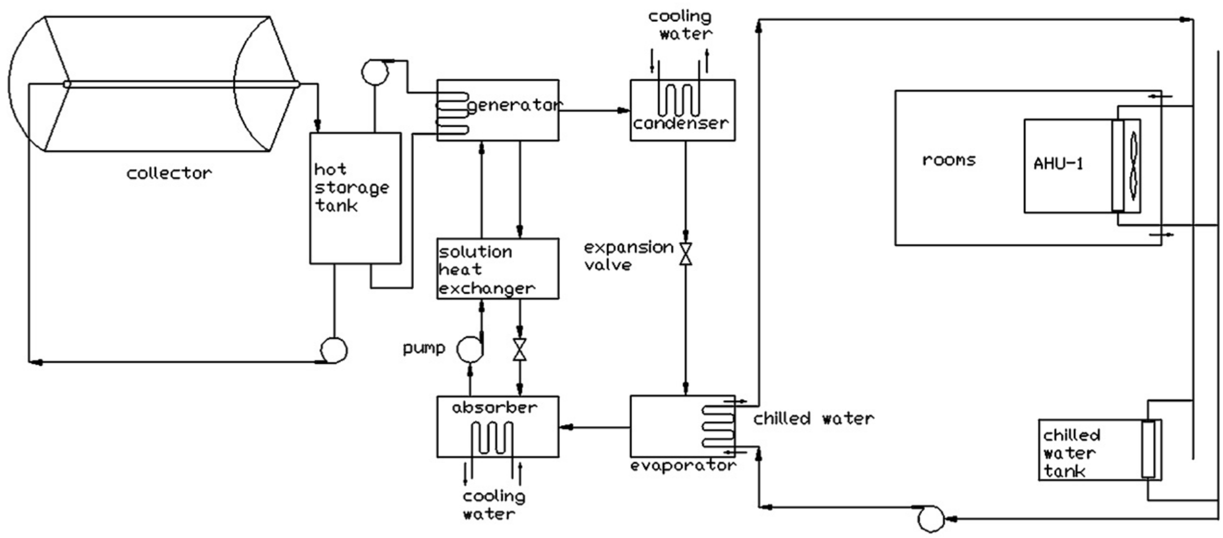

Fig. 1. Schematic diagram of an absorption chiller integrated with a solar concentrator and storage tank.

absorption cooling, and finally, on subjects with a thrust on thermal storage integrated cooling systems are reviewed. Also described are some of the analyses of the demonstration projects carried out by researchers on aspects related to solar absorption cooling. Koroneos et al. [58] presented the exergy, environmental and economic evaluation of the single effect water–lithium bromide solar cooling installation in a medical center.

In solar absorption cooling, various theoretical studies have focused mainly on simulation using Transient Simulation software, TRNSYS. A thermodynamic analysis and simulation studies are essential for the cost effective design of a solar cooling system. Tsoutsos et al. [59] have simulated a complete system comprising a solar collector, a storage tank, a backup heat source, cooling tower and a LiBr–H_2O absorption chiller using the TRNSYS. They observed that the investment cost would be quite high, but compensated by the highest environmental benefits, lower payback time and the highest total annual savings. Xavier Garcia Casals [60] has presented the criteria and outcomes of the TRNSYS dynamical simulation of the solar heating and cooling installations implemented in Spain, and analyzed the findings in comparison with other solar cooling options. A transient solar collector-driven water heating and absorption cooling plant mathematical model was developed by Vargas et al. [61] to obtain the system response in time and to calculate the second law efficiency of the entire system as functions of operating and design parameters. Kumar et al. [62] have suggested high flow ratios to extend the daily operating time of a solar-driven water–lithium bromide absorption system. A dynamic model of a solar cooling plant has been developed and validated with real data by Zambrano et al. [63]. Ortiz et al. [64] have reported the outcomes of a numerical model of a solar-thermal-assisted heating, ventilation and air conditioning system in a 7000 m^2 educational building, situated in a high-desert climate. The model points at an increase in the performance of the system with decreasing heat medium temperature. Osman [65] has described the design and operation of a solar absorption cooling system and a solar PV-powered cooling system in a research establishment in Kuwait.

5. Cool thermal energy storage

Storing cool energy produced during sunshine hours in a cool thermal storage tank, either in a sensible heat form or in a latent heat form is yet another option of storing energy. Cool thermal energy storage (CTES) has recently attracted increasing interest in industrial refrigeration applications, such as process cooling, food preservation and building air conditioning systems. CTES appears to be one of the most appropriate methods for correcting the mismatch that occurs between the supply and demand of energy. Cool energy storage requires a better insulation tank as the energy available in the cool state is expensive, compared to the heat available in a hot storage tank.

Sensible heat chilled water storage systems utilizing stratification tanks were studied by Tran et al. [66] and Musser and Bahnfleth [67]. Nelson et al. [68] have pointed out that the percent cold recoverable in a discharge cycle increases with increasing initial temperature difference, aspect ratio and flow rate. Karim [69] has indicated that partial discharging in one discharge cycle involves a relatively longer residence time of cool water in storage that leads to a significant decrease in thermal efficiency, as the temperature of the chilled water in the tank increases because of heat conduction through the walls. Hence, for any practical requirements the storage system should be designed with several tanks, so that based on the cooling requirement, the required number of tanks can be charged and discharged.

Storing energy in the latent form has its own advantage, compared to the energy storage in a sensible heat form. Fukusako and Yamada [70] have reviewed the transport phenomena observed during the melting of the PCM inside ducts and over external bodies. Ermis et al. [71] have proposed a feed-forward back-propagation artificial neural network algorithm, for the heat transfer analysis of the phase change process in a finned tube latent heat thermal energy storage system. They have compared the performance of the model with experimental data and the numerical results obtained through heat transfer analysis with ethyl alcohol as the HTF and pure water as the PCM. For a similar PCM–HTF combination, Erek and Dincer et al. [72] have dwelt on the entropy and exergy efficiency analysis of a shell and tube latent heat storage system. Ezan et al. [73] investigated the energetic and exergetic performances of a shell and tube latent energy storage system using water as PCM and ethylene glycol as the HTF. They concluded that for the charging period, the exergetic efficiency increased with the increase in the inlet temperature and the flow rate. For the discharging period, irreversibility increased as the temperature difference between the melting temperature of the PCM and the inlet temperature of the HTF increased, and hence the exergy efficiency increased.

Bedecarrats et al. [74] presented the experimental results of the charge and discharge modes of LHTS for air condition-

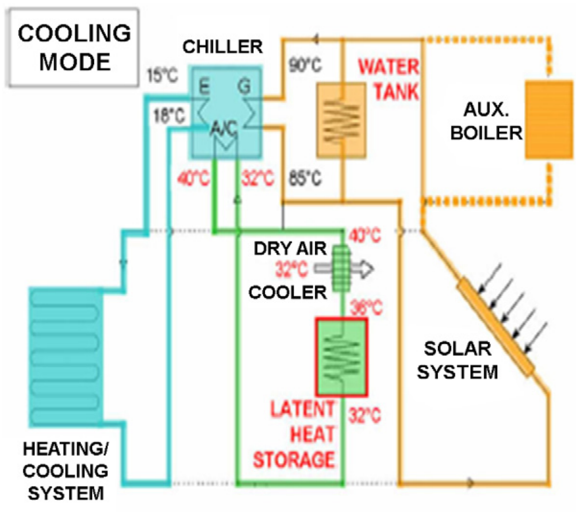

Fig. 2. Solar heating/cooling system with an absorption chiller and latent heat storage in the cooling mode [80].

ing/refrigeration applications using PCM encapsulated spherical capsules. The improvement in the heat transfer rates in storage units employing multiple PCMs, inserting a metal matrix into the PCM, using PCM dispersed with high conductivity particles, and micro-encapsulation of the PCM, have been studied and reported by various researchers. Velraj et al. [75] carried out investigations in CTES integrated with a large air conditioning system located at Chennai, India. They have concluded that the integration of CTES integrated systems in applications such as food preservation, would prove beneficial. Cheralathan et al. [76] investigated the performance of an industrial refrigeration system integrated with CTES. The authors have indicated significant savings in capital and operating cost, in thermal storage integrated systems. The size of the PCM based CTES system was also considerably reduced when compared with that of a chilled water system. Wu et al. [77] investigated the effects of the flow rate, inlet temperature of the HTF, porosity of the packed bed consisting of *n*-tetradecane, and the size of the capsules on the dynamic performance of the cool thermal storage system during the charging and discharging process. Fang et al. [78] reported better performance and stable charging and discharging periods of an experimental cool storage air-conditioning system, with a spherical capsules packed bed. The numerical heat transfer analysis of an encapsulated ice thermal energy storage system with a variable heat transfer coefficient by Erek and Dincer [79], has revealed that the solidification process is chiefly governed by the magnitude of the Stefan number, capsule diameter and capsule row number.

Helm et al. [80] have described the operation of an absorption cooling system, that involves latent heat storage supporting the heat rejection of the absorption chiller, in conjunction with a dry cooling system as shown in Fig. 2. They have indicated low temperature latent heat storage together with a dry air cooler, as a promising alternative to the conventional wet cooling tower, as it substantially reduces the over-sizing of the solar collector system.

Berlitz et al. [81] have introduced one more concept of storing a cool refrigerant internally in the absorption chiller system, in order to ensure a continuous supply of cool energy with minimal dependence on an external heat source to normalize fluctuation in the availability of solar energy. Rizza [82] has observed that the storage volumetric efficiency for the LiBr/H_2O system is greater than or comparable to, that of a thermal storage system based on water–ice, and that it far exceeds the value of a thermal storage system based on liquid water.

6. Cascaded storage system for solar cooling

The intermittent nature of solar energy is one of the major technical constraints that prevent the successful wide implementation of solar energy technologies. Significant economic and environmental benefits can be obtained with effective collection, storage and efficient utilization of solar energy. A cascaded storage system offers vast potential for the improvement of a solar cooling system performance. In a cascaded storage system, PCMs with different melting temperatures are arranged in a series to store heat in different temperatures. In comparison with a conventional single PCM based storage system, a cascaded multiple PCM based storage system would improve solar collecting efficiency as the lower temperature at the bottom of the tank is connected to the inlet of the solar collector. The numerical results from the parametric study investigated by Shaikh and Lafdi [83] indicated that the total energy charged rate can be significantly enhanced by using composite PCMs as compared to the single PCM. Gong and Mujumdar [84] proposed a solar receiver store consisting of multiple PCMs and found that the fluctuation of the outlet temperature of the HTF can be greatly dampened by using multiple PCMs compared with a single PCM.

Deng et al. [85] have outlined the need for R&D in the cascade utilization of thermal energy in combined cooling, heating and power systems. Gordon and Ng [86] have proposed a high efficiency solar cooling involving a thermodynamic cascade that comprises of solar-fired gas micro-turbine producing electricity that drives a mechanical chiller, with the turbine heat rejection running an absorption chiller. Depending on the stored temperature level and the temperature required in the generator of an absorption cycle, different solar absorption cooling equipments can be employed to facilitate the use of stored heat. Multiple effect absorption chillers have a higher COP but can operate only at high temperatures. Though half and single effect absorption cooling systems have lower COPs, they are advantageous in utilizing the stored heat at a low temperature. A combination of the multiple effect and half/single effect can thus be chosen, based on stored temperature availability. Technical considerations favor such a combination of thermally driven cooling technologies with a multiple PCM based storage system. However, the cost and space requirements might be a limiting factor. The thermoeconomic optimization of such a system would lead to a prudent design, optimization and selection of equipments. However, its economic viability needs further study.

7. Applications

Absorption cooling is one of the promising technologies with wide scope for practical applications. One of its main advantages is that it is best suited for solar thermal applications. Pongtornkulpanich et al. [87] reported their experiments of a solar-driven 10-TR H2O/LiBr VAC cooling system installed at the School of Renewable Energy Technology (SERT), Naresuan University, Phitsanulok, Thailand. Demonstration projects based on a solar-powered absorption cooling system installed in China, have been presented by Zhai and Wang [88]. The possibility of saving in total costs in CO_2 emissions of integrated solar absorption cooling and heating systems for residential, hotel and office applications in three different locations using TRNSYS was presented by Mateus and Oliveira [89]. Desideri et al. [90] have analyzed the technical and economic feasibility of replacing/integrating existing compression refrigeration systems with solar absorption cooling systems for meat refrigeration and a hybrid thermo-solar trigeneration plant for the heating and cooling demands of a hotel. The design, control, analysis and optimization of an experimental 30 kW solar absorp-

tion cooling facility to cool classrooms without a backup system during the occupancy period, has been presented by Marc et al. [91]. The storage capacities of the tanks are 1500 and 1000 m^3, for the hot and cold water tanks respectively, providing 45 mins autonomy in hot and cold water production.

8. Conclusions

In this paper, an extensive review of the technologies related to the better utilization of solar energy for the production of cool energy is presented. It is understood from the review that thermal storage is essential in the solar circuit, in order to take maximum advantage of the solar resource and control differences between the cooling/heating demand and solar radiation availability. Thermal storage integrated solar cooling systems increase the cooling availability, capacity and improve the overall performance. Absorption chillers have gained considerable attention among researchers. More research and development on enhanced solar cooling techniques coupled with a simpler, energy efficient and cost effective thermal storage system, possessing higher energy density would lead to economic competitiveness. It would also assist in the further development of affordable thermal storage systems, and increase the market penetration of solar cooling. Solar cooling is an emerging market with several actors with promising potential and scope for innovation. There are many pilot and demonstration experiences in solar cooling systems. However, the next few years will be the most decisive for the success of solar cooling technologies that depend on the encouragement and promotional schemes offered by the policymakers, and the efforts undertaken by the manufacturers to improve the cost efficiency as well in developing better technologies.

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